

Passive Thermal Logic and Conservation Significance of Ethiopian Tukul Architecture in a Warm Semi-Arid Region

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Abstract- Ethiopian Tukul houses embody a close relationship among local materials, craft practice, spatial organization and climate-responsive building. This study examines the passive thermal logic and conservation significance of Tukul architecture in Kechema Ward, East Shewa, Oromia, with attention to the circular plan, earthen and wattle-and-daub walls, conical thatched roof, restricted openings, roof-wall air paths and locally available materials. The investigation adopts a qualitative architectural-heritage approach based on author-prepared field drawings from a 2023 field study and a structured synthesis of 35 peer-reviewed studies, with emphasis on Ethiopian, sub-Saharan African and recent architectural-heritage research. Architectural features are interpreted through heat-transfer and environmental mechanisms and examined through cross-study triangulation. The synthesis indicates that the Tukul envelope functions as a coordinated passive system in which earthen walling can buffer diurnal heat flow, deep thatch and eaves limit direct solar loading, and the doorway and roof-wall gap support controlled air exchange under favourable outdoor conditions. Conservation priorities therefore extend beyond the circular silhouette to compatible earthen finishes, roof craft, the raised base, ventilation details and the knowledge required for maintenance. The study presents a heritage-centred framework for understanding the environmental logic of Tukul architecture and for guiding conservation and climate-responsive adaptation.

Keywords- Ethiopian Tukul; vernacular architecture; architectural heritage; passive thermal design; earthen construction; thermal buffering; climate adaptation; East Shewa; Oromia.

- Tukul environmental behaviour is interpreted through the documented interaction of form, earth walling, thatch roofing and controlled openings.
- A 35-study evidence synthesis triangulates the identified mechanisms and gives greater weight to Ethiopian and sub-Saharan African evidence.
- The analysis links passive thermal logic with material compatibility, repair practice, craft knowledge and architectural-heritage significance.
- The conservation framework distinguishes documented Kechema evidence from literature-informed risks associated with climate change and modernization.
- Future assessment should combine a defined field sample, seasonal thermal and indoor-air-quality monitoring, material testing and calibrated simulation.

Graphical abstract



Abbreviation	Meaning
ACH	Air changes per hour
MRT	Mean radiant temperature
RH	Relative humidity

Abbreviation	Meaning
TEK	Traditional ecological knowledge
U-value	Overall thermal transmittance

Graphical abstract. Author-prepared 2023 field drawings are connected to passive environmental mechanisms and conservation attributes examined in the study.

I. INTRODUCTION

Vernacular buildings are often described as architecture produced through accumulated local knowledge rather than through formal professional design. Their value lies not only in appearance but in the way construction, available resources, family practices and environmental conditions are negotiated over generations. Oliver (2003) and Rapoport (1969) approached vernacular dwelling from complementary disciplinary positions, and both treated the house as an expression of culture embedded in place. For architectural heritage research this point is important: preserving a vernacular dwelling cannot be reduced to keeping an isolated object unchanged. Its material logic, construction sequence, repair practices and environmental intelligence also need to be understood.

Climate change adds urgency to that task. Existing buildings are being exposed to warmer conditions, altered rainfall regimes and changing patterns of occupancy, while contemporary replacement housing frequently depends on materials and systems that were not developed for local climatic rhythms. Crawley (2008) showed that future climate conditions can materially affect building performance, and Robert and Kummert (2012) argued that low-energy buildings should be designed for future rather than historical climate. These concerns are especially relevant to vernacular heritage, where thermal performance is closely tied to the physical properties of traditional materials and to behavioural patterns that may themselves be changing.

A substantial body of building-science research has demonstrated that traditional construction can contain passive strategies with contemporary relevance. Zhai and Previtali (2010) classified energy-related characteristics of ancient vernacular architecture and showed the value of evaluating inherited forms using modern performance concepts. Reviews by Chandel, Sharma, and Marwah (2016) similarly identified

orientation, thermal mass, openings, spatial organization and roof construction as recurring contributors to indoor comfort. The significance of such work is not that every traditional building is automatically comfortable or sustainable, but that long-lived building traditions provide testable design hypotheses rooted in climatic adaptation.

Ethiopia presents an especially rich setting for this discussion. Its architectural traditions vary substantially in form, material and settlement pattern. Datta and Gruber (2021) and the earlier documentation of Gebremedhin (1971) show that the circular Tukul is not a single immutable prototype; dimensions, wall systems, roof materials and internal organization change with geography, resources and social practice. Recent Ethiopian evidence also strengthens the environmental context. Hailu, Gelan, and Girma (2021) measured indoor conditions in traditional and modern buildings in a hot-arid Ethiopian setting, while Yadeta et al. (2023) developed an adaptive-comfort model from naturally ventilated residential buildings in Jimma and Asres et al. (2026) reported a locally calibrated comfort model for Ethiopian social housing. The latter two studies are not Tukul analogues, but they demonstrate why comfort thresholds and occupant adaptation should be established locally rather than transferred uncritically from another climate or building type.

The case study focuses on traditional Tukul houses in Kechema Ward, East Shewa, Oromia. In this article, Tukul refers specifically to the locally documented circular, single-storey dwelling tradition represented in the 2023 field drawings and is used in this regional case-study sense. The documented variants use timber or reed frameworks finished with earth, steep grass-thatch roofs, restricted openings and a low doorway. Some drawings show an internal partition, central post and hearth, while others are largely undivided. Together, these records provide the architectural basis for examining environmental behaviour, material logic and conservation value.

The analysis proceeds from directly documented architectural features to their environmental interpretation. Form, material arrangement, construction details, spatial organization and openings are read in relation to solar exposure, thermal storage, insulation, moisture behaviour and air movement. These interpretations are then triangulated with published monitoring and simulation studies from Ethiopia, sub-Saharan Africa and comparable climatic settings. This approach keeps the paper

centred on the architectural evidence while supporting a physically grounded discussion of passive performance.

This evidence-constrained approach is especially relevant to living architectural heritage. A Tukul is more than a recognizable circular silhouette: its significance lies in the relationship among local materials, construction sequence, recurrent repair, household use and climatic adaptation. Recent Ethiopian documentation research by Asfha, Okazaki, and Girmay (2026) illustrates the value of combining archival evidence with systematic recording of vernacular buildings threatened by transformation, while Carlos et al. (2022) emphasize that earthen heritage must be understood through material, technical and community dimensions. These perspectives allow the Kechema case to address not only plausible passive mechanisms, but also which attributes merit conservation and which uncertainties must be resolved before interventions are recommended.

The study therefore has four connected purposes: to document the architectural characteristics represented in the Kechema field documentation; to interpret the passive thermal mechanisms associated with form and envelope; to triangulate those interpretations with measured, simulated and field-based studies, particularly from Ethiopia and sub-Saharan Africa; and to identify conservation priorities together with a practical agenda for climate-responsive heritage management.

II. LITERATURE REVIEW

Vernacular architecture as environmental and cultural knowledge

Research on vernacular architecture has moved progressively from typological description toward interdisciplinary evaluation. Early cultural accounts established that house form results from more than climate alone: kinship, belief, economy, construction skills and social conventions also shape the dwelling. Building-science studies later added measurable variables such as indoor air temperature, relative humidity, thermal lag, surface temperature and comfort response. The most useful recent work combines these perspectives rather than setting them against one another. In a heritage context, a wall can be simultaneously a thermal mass, a product of local soil and craft knowledge, a maintenance responsibility and a culturally meaningful boundary.

The literature also warns against romanticizing vernacular buildings. Climate responsiveness is a property to be

demonstrated, not presumed. Singh, Mahapatra, and Atreya (2010), Dili, Naseer, and Varghese (2010), and Shanthi Priya et al. (2012) used field-based approaches to show how traditional envelopes can moderate indoor conditions, but their results are specific to climate, material and use. Singh, Mahapatra, and Atreya (2011) further demonstrated that passive features operate as systems rather than isolated devices. This systems perspective is central to the Tukul case: the round plan, wall, roof, eaves, openings and hearth interact, and their performance cannot be inferred reliably by considering a single component alone.

Material transition is another recurring theme. Shastri, Mani, and Tenorio (2014) found that changes introduced during modernization can alter the thermal behaviour of vernacular dwellings, while Praseeda, Mani, and Reddy (2014) linked material choices to both operational and embodied energy. These findings are important for conservation because replacing an earthen or plant-based component with a seemingly durable industrial material may affect moisture transfer, thermal storage, repairability and visual character at the same time. Conservation decisions should therefore consider environmental compatibility alongside structural and aesthetic criteria.

Passive thermal strategies in hot and seasonally warm climates

Across hot-arid and hot-season climates, vernacular dwellings repeatedly employ a limited family of physical strategies: compact geometry, thermal mass, shaded openings, insulating roof layers and ventilation timed to favourable outdoor conditions. Salgin et al. (2017) interpret such features as components of regional housing sustainability. In sub-Saharan Africa, Widera (2021) compared six vernacular dwelling types and showed that comfort and thermal performance must be read together with local climate, envelope construction, ventilation and indoor environmental conditions. Rincón et al. (2019) likewise demonstrated through passive-design analysis that earthen dwellings in sub-Saharan Africa can be improved without assuming energy-intensive conditioning. These studies are more useful to the Kechema case as evidence for mechanisms than as sources of transferable numerical values. These studies also reveal why a simple label such as 'thick wall' is insufficient. Thermal mass is useful when it delays and attenuates heat flow across a meaningful day-night temperature swing; under continuously hot and humid conditions, the same strategy may be less effective unless combined with ventilation.

Roof performance depends on solar absorptance, thickness, air pockets, moisture and ventilation at the eaves. Small openings may reduce solar and dust entry but may also restrict air movement. A sound analysis must therefore state the mechanism and its boundary conditions rather than treating every traditional feature as universally beneficial.

The literature also shows that environmental performance cannot be separated from conservation practice. Tawayha, Bragança, and Mateus (2019) linked vernacular characteristics with broader sustainability assessment, and Carlos et al. (2022) developed a referential framework for earthen vernacular heritage that brings together material behaviour, intervention principles and community knowledge. Henna, Saifudeen, and Mani (2021) extended the discussion to climate resilience, showing that inherited strategies may respond differently as climate and occupancy change. The implication for Tukul conservation is therefore conditional rather than romantic: inherited features can remain valuable, but their function and durability should be tested before either preservation or replacement is prescribed.

Thermal comfort, modernization and passive cooling

The indoor-comfort literature provides an important empirical basis for interpreting the Tukul. Hailu, Gelan, and Girma (2021) compared traditional and modern buildings in a hot-arid Ethiopian context using environmental measurements. Yadeta et al. (2023) extended Ethiopian evidence through an eight-month adaptive-comfort study in naturally ventilated housing in Jimma, and Asres et al. (2026) further demonstrated that local behavioural adaptation matters in Ethiopian residential comfort assessment. Together, these studies establish a regional basis for reading temperature, humidity, radiant conditions, air movement and occupant response in relation to vernacular form and materiality. Widera (2021) also draws attention to indoor environmental quality in sub-Saharan vernacular dwellings, which is particularly relevant to Tukul houses containing a hearth where thermal benefit, ventilation and smoke exposure interact.

More recent work continues to refine this evidence. Al-Hashim, Benkari, and Al-Saadi (2024) combined field surveys with analysis of vernacular houses in Oman; Chkeir et al. (2024) compared traditional and contemporary houses in Byblos; and Ergün and Bekleyen (2024) proposed a taxonomic reading of passive strategies in hot-dry traditional architecture. Widera (2021) provides a more directly regional comparison across

western sub-Saharan African vernacular dwellings, while Yadeta et al. (2023) adds Ethiopia-specific adaptive-comfort evidence. Together, these studies support comparison of mechanisms and measurement approaches while retaining climatic and building-type specificity.

The newest studies reinforce the continuing relevance of empirical comfort assessment and occupant/building comparison. Abdallah et al. (2025) evaluated strategies for improving human thermal comfort in vernacular spaces in hot-arid Egypt, while Ibrahim and Abdullah (2026) compared traditional and contemporary houses in Erbil's hot-dry climate. For the Kechema case, these studies strengthen cross-study triangulation by clarifying how envelope form, materiality, ventilation and use interact under warm climatic conditions.

Vernacular built heritage, documentation and conservation

Thermal value is only one component of architectural heritage significance. Datta and Gruber (2021) show that Ethiopian building traditions are inseparable from material supply and construction technique. Sahle and Saito (2021) and Kebede, Amsalu, and Yosef (2024) show that Ethiopian cultural landscapes and vernacular architecture are embedded in wider socio-cultural systems. More recently, Asfha, Okazaki, and Girmay (2026) demonstrate the value of archival research and systematic digital documentation for preserving Ethiopian vernacular architecture under transformation. For Tukul heritage, environmental performance should therefore be conserved together with construction knowledge, regional identity and patterns of use.

Contemporary heritage methods provide useful tools for such work. Arias Tapiero et al. (2025) developed an ICT-enhanced approach for regional characterization of vernacular built heritage, emphasizing systematic documentation and inventory. Their later methodology for analysing contemporary transformation (Arias Tapiero, Ortega, and Vasconcelos 2025) treats alteration as something that can be recorded and assessed rather than described impressionistically. Sánchez-Calvillo, Ortega Heras, and Alonso Guzman (2025), although focused on seismic vulnerability of Mexican adobe buildings, likewise demonstrate how morphological and construction features can be translated into transparent assessment criteria.

Climate adaptation and conservation are now increasingly discussed together. Sanagustín-Fons et al. (2025) analyse sustainable building techniques within a cultural-heritage and

climate-adaptation framework. Curk et al. (2025) stress that vernacular knowledge and skills are themselves a form of heritage protection, an argument directly relevant to Tukul thatching, timber tying and earthen finishing. Earlier work by Correia and Walliman (2014) on earthen-built heritage further underlines that interventions must respect material behaviour and inherited construction logic.

For the Kechema Tukul, these heritage studies shift the unit of analysis from 'thermal feature' to 'conservation attribute'. A thick mud-finished wall matters not only because of heat storage; it also records a local material chain, workmanship, maintenance cycle and visual language. A conical thatch roof is not merely insulation; it is a geometrically organized craft system of rafters, rings, ties and renewable covering. The

thermal and heritage readings are therefore complementary, and this integration forms the conceptual basis of the present study.

Synthesis of 35 peer-reviewed studies

Table 1 summarizes 35 peer-reviewed studies retained for comparative synthesis. Rather than functioning as a catalogue, the evidence matrix is read thematically across four questions: passive thermal mechanisms; Ethiopian and sub-Saharan African comfort evidence; modernization and climate resilience; and conservation/documentation methods. Foundational books and Ethiopia-specific documentary sources are cited separately and are not counted among the 35 studies.

Table 1. Comparative evidence matrix of 35 peer-reviewed studies used for thematic synthesis and cross-study triangulation.

Study	Context	Approach	Relevance to this paper
Crawley (2008)	Building performance / future climate	Simulation-oriented climate sensitivity	Shows that changing climate can alter building performance; supports future-climate testing.
Zhai & Previtali (2010)	Ancient vernacular buildings	Characteristic categorization and energy evaluation	Establishes a framework for translating vernacular features into energy-performance mechanisms.
Singh et al. (2010)	North-East India	Field thermal performance and comfort evaluation	Empirical evidence that traditional materials and form can moderate indoor thermal conditions.
Dili et al. (2010)	Kerala, India	Occupant questionnaire and building comparison	Links measured/experienced comfort with traditional residential construction.
Singh et al. (2011)	North-East India	Solar-passive feature analysis	Shows passive elements acting as a coordinated environmental system.
Robert & Kummert (2012)	Future-climate low-energy design	Building-energy analysis	Demonstrates need to design and evaluate for future rather than historical climate.
Shanthi Priya et al. (2012)	Coastal Tamil Nadu, India	Qualitative and quantitative thermal analysis	Provides evidence on roof, envelope and passive features in vernacular housing.
Shastry et al. (2014)	Warm-humid India	Field comparison across modernization transition	Shows modernization can alter thermal comfort and environmental performance.
Praseeda et al. (2014)	Indian vernacular dwellings	Embodied/operational energy assessment	Connects material transition with energy and comfort implications.
Correia & Walliman (2014)	Earthen heritage	Conservation criteria	Supports compatibility-based intervention in earthen-built heritage.
Chandel et al. (2016)	Global vernacular review	Systematic review	Identifies recurring energy-efficient features relevant to indoor comfort.
Salgin et al. (2017)	Eastern Black Sea housing	Sustainability feature assessment	Links local materials and inherited form with environmental sustainability.
Widera (2021)	Western sub-Saharan Africa	Comparative field assessment of six vernacular dwelling types	Regional evidence that thermal mass, shading, ventilation and indoor environmental quality must be assessed as an interacting system.

Study	Context	Approach	Relevance to this paper
Rincón et al. (2019)	Sub-Saharan Africa	Passive-design analysis of earthen dwellings	Direct regional relevance for earthen envelopes and low-energy comfort improvement.
Tawayha et al. (2019)	Mediterranean city	Comparative sustainability study	Connects vernacular morphology with multi-dimensional sustainability.
Carlos et al. (2022)	Earthen vernacular heritage	Reflective literature review and conservation framework	Connects earthen material performance, compatible intervention, maintenance and community knowledge.
Hailu et al. (2021)	Hot-arid Ethiopia	Indoor thermal monitoring and comparison	Provides Ethiopian empirical support for traditional-building thermal moderation.
Henna et al. (2021)	Three climatic zones	Climate-resilience comparison	Tests resilience of vernacular and modernizing dwellings under climate change.
Izadpanahi et al. (2021)	Traditional Iranian houses	Passive-cooling strategy synthesis	Supports mechanism-based reading of shading, mass and ventilation.
Yadeta et al. (2023)	Jimma, Ethiopia	Eight-month adaptive thermal-comfort field study in naturally ventilated housing	Ethiopia-specific evidence that local comfort response and occupant adaptation should be measured rather than transferred from other climates.
Datta & Gruber (2021)	Ethiopian architectural traditions	Comparative construction study	Provides Ethiopia-specific evidence on materials, techniques and regional diversity.
Sahle & Saito (2021)	Gurage cultural landscape, Ethiopia	Cultural-landscape mapping	Shows built heritage embedded in wider socio-ecological landscape.
Asfha et al. (2026)	Təgray, Ethiopia	Archival research, field documentation and digital recording of vernacular architecture	Shows current Ethiopian need for systematic vernacular documentation and conservation under transformation pressures.
Al-Hashim et al. (2024)	Al Batinah, Oman	Field survey and sustainability analysis	Recent hot-arid field evidence on vernacular sustainable features.
Chkeir et al. (2024)	Byblos, Lebanon	Traditional vs contemporary thermal-comfort comparison	Supports mechanism-level comparative triangulation across site contexts.
Ergün & Bekleyen (2024)	Hot-dry traditional architecture	Passive-design taxonomy	Provides structured classification of passive strategies.
Asres et al. (2026)	Jimma, Ethiopia	Field thermal-comfort and behavioural-adaptation model in social housing	Recent Ethiopian non-vernacular context reinforcing the need for locally calibrated comfort assessment and behavioural data.
Kebede et al. (2024)	Gurage, Ethiopia	Qualitative vernacular-heritage assessment	Connects Ethiopian vernacular identity with sustainability and future development.
Arias Tapiero et al. (2025)	Regional vernacular built heritage	ICT-enhanced characterization	Offers systematic documentation principles suited to heritage inventories.
Sanagustín-Fons et al. (2025)	Cultural heritage and climate adaptation	Socio-environmental analysis	Links sustainable building techniques with climate adaptation and heritage values.
Curk et al. (2025)	Serbian vernacular heritage	Knowledge/skills conservation study	Treats craft knowledge as a conservation object, relevant to Tukul construction skills.
Arias Tapiero et al. (2025b)	Vernacular settlements under transformation	Impact-assessment methodology	Provides a transparent way to assess modernization-related alteration.

Study	Context	Approach	Relevance to this paper
Sánchez-Calvillo et al. (2025)	Mexican vernacular adobe	Comparative vulnerability assessment	Demonstrates feature-based assessment for earthen vernacular buildings.
Abdallah et al. (2025)	Hot-arid Egypt	Thermal-comfort improvement study	Recent quantitative evidence for climate-responsive vernacular spatial strategies.
Ibrahim & Abdullah (2026)	Erbil, Iraq	Traditional vs contemporary indoor comfort study	Latest comparative evidence reinforcing the need for direct monitoring and occupant-based assessment.

III. RESEARCH GAP, NOVELTY AND AIM

Research gap

The literature demonstrates a mature understanding of passive strategies in vernacular architecture, yet three research needs remain when attention is narrowed to the Kechema Tukul. First, Ethiopian studies of measured comfort are growing, including Hailu et al. (2021), Yadeta et al. (2023) and Asres et al. (2026), while detailed case-based thermal interpretation of Kechema Tukul architecture remains limited. Second, architectural descriptions often identify thick earthen walls, thatch or small openings without explicitly linking each feature to a physical mechanism and a level of evidence. Third, thermal-performance and heritage-conservation studies are frequently treated separately even though the same roof, wall and opening details carry environmental, material and cultural value.

The Kechema case provides an opportunity to address these needs by connecting field-based drawings and construction descriptions to physically plausible thermal mechanisms, triangulating those mechanisms with empirical literature, and translating the resulting evidence into conservation priorities. The paper therefore treats architectural documentation, passive environmental reasoning and heritage significance as parts of one analytical framework rather than as separate lines of inquiry.

A further unresolved question concerns climate change and modernization. Traditional passive systems evolved under historical climatic conditions, material supply chains and patterns of use. Their continued effectiveness cannot be assumed as night-time temperatures, rainfall regimes, maintenance practices and household expectations change. For Tukul heritage, adaptation may be necessary, but interventions should be tested because changes in roof covering, surface

permeability, opening size or drainage can alter environmental performance as well as authenticity.

Novelty statement

The novelty of the study lies in integrating passive-thermal interpretation and architectural-heritage assessment for the Kechema Tukul within one evidence-ranked framework. Each environmental claim is anchored first to a documented 2023 architectural feature, then triangulated with peer-reviewed measured or simulated evidence, and finally translated into conservation significance and intervention priority. The resulting approach combines Ethiopia-focused comparison, mechanism-based thermal reasoning and conservation planning in a form that can also support the assessment of other vernacular buildings documented through architectural survey.

Aim and objectives

The aim is to evaluate the passive thermal logic and conservation significance of traditional Tukul architecture in Kechema Ward, East Shewa, Oromia, using field-based architectural documentation and a current body of peer-reviewed literature.

- Document the form, spatial arrangement, wall system, roof assembly, openings and local materials represented in the case-study drawings.
- Interpret the principal passive thermal mechanisms associated with the documented form, materials, roof system and openings.
- Triangulate the interpretations through comparison with empirical and simulation-based studies of vernacular buildings in Ethiopia, sub-Saharan Africa and comparable climates.
- Identify conservation attributes, vulnerabilities and adaptation priorities for Tukul architectural heritage.
- Define a future field-monitoring and simulation programme capable of testing present and future thermal performance quantitatively.

IV. MATERIALS AND METHODOLOGY

Study design and evidence hierarchy

The investigation follows a qualitative case-study design supported by structured literature review and cross-study triangulation. Three levels of evidence are distinguished. First, the field-based drawings and architectural descriptions provide direct evidence of form, spatial arrangement and construction. Second, peer-reviewed studies provide measured, simulated or systematically documented evidence for comparable passive mechanisms. Third, conceptual and conservation literature is used to interpret heritage significance. Conclusions are phrased according to the strongest level of evidence available for each claim.

This hierarchy keeps the interpretation proportional to the available evidence. An earthen wall, for example, is discussed as a thermal buffer through its documented mass and construction together with established heat-storage mechanisms from previous studies. In the same way, roof depth, eaves, restricted openings and high-level air paths are interpreted through their physical roles and comparative evidence. The method therefore emphasizes mechanism-level reasoning, traceable evidence and conservation relevance.

Study area and climatic context

The field documentation identifies the case-study area as Kechema Ward in East Shewa, Oromia, Ethiopia, and records an approximate field point at 9.6833° N, 38.6500° E with an elevation of about 2,812 m. Figure 1 presents this coordinate at national scale to establish the geographical context of the case study. The locator is used as a regional reference for discussing settlement setting, climatic exposure and the relationship between the Tukul building tradition and the East Shewa landscape.

The field documentation situates Kechema within a warm semi-arid setting characterized by marked daily and seasonal variation. At the broader East Shewa scale, Balcha, Wami, and Game (2024) report pronounced seasonal rainfall variability, with the main wet period concentrated in the boreal summer months. This regional climatic context is relevant to roof drainage, earthen-wall weathering, material moisture, ventilation timing and the seasonal operation of passive strategies. The architectural analysis therefore interprets the

Tukul as a climate-responsive system shaped by warm conditions, diurnal change and seasonal rainfall.



Figure 1. National locator of the approximate Kechema field-study coordinate reported in the 2023 case record. The figure is a locator rather than a cadastral or administrative-boundary map.

Case-study architectural evidence

The architectural evidence consists of drawings prepared by the first author from a 2023 field study in Kechema Ward. The documentation represents recurring construction and spatial variants, including an unpartitioned circular dwelling, a partitioned arrangement, wattle-and-daub wall construction, roof framing and the stone base. Figures 2-5 present these author-prepared records after graphic cleaning for legibility. The drawings are used as typological case documentation to examine how geometry, material assembly, spatial organization and construction practice contribute to the environmental and heritage character of the Tukul.

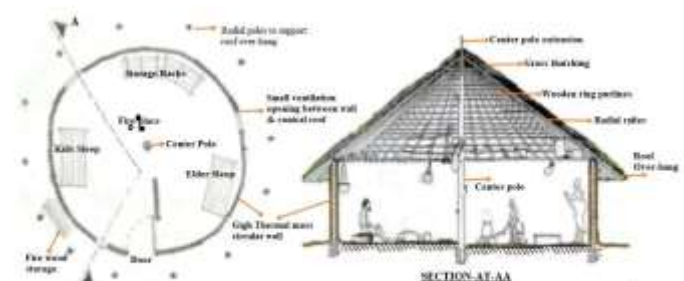


Figure 2. Plan and section of a common single-room circular Tukul without an internal partition, showing the central post, hearth, storage zones, wall-roof opening and conical roof structure. Source: author-prepared field documentation, 2023.

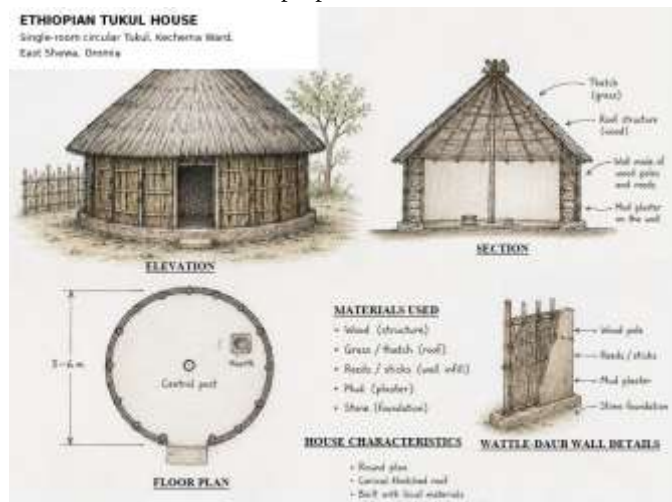


Figure 3. Architectural and construction details of a single-room Tukul, including elevation, section, floor plan, local materials and wattle-and-daub wall construction. Source: author-prepared field documentation, 2023.

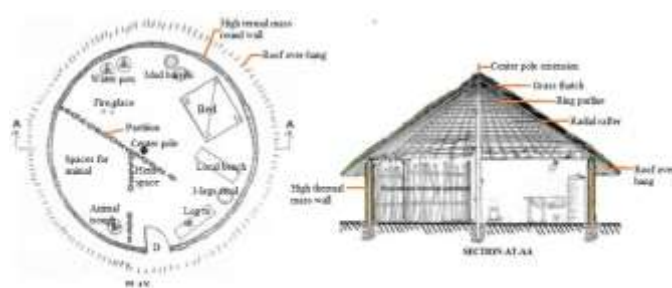


Figure 4. Plan and section of a circular Tukul with an internal partition, illustrating spatial subdivision within the single-room envelope. Source: author-prepared field documentation, 2023.

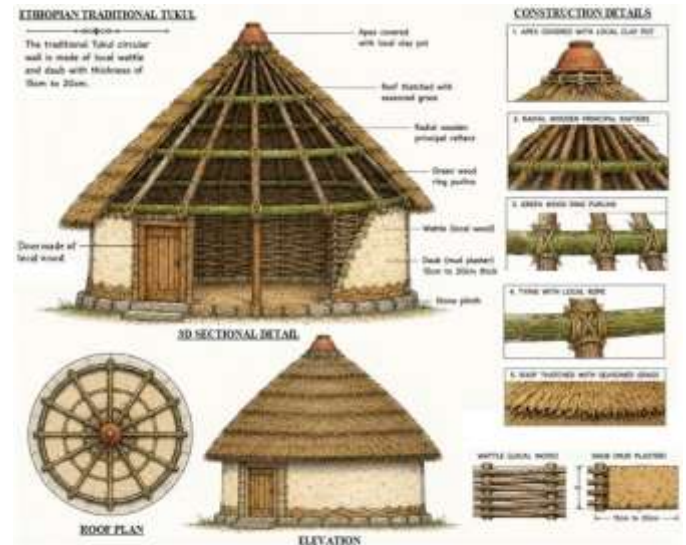


Figure 5. Three-dimensional construction details of the Tukul roof and wall assembly, including radial rafters, ring members, thatch, wattle-and-daub walling and the stone plinth. Source: author-prepared field documentation, 2023.

Literature-review protocol

The literature review was structured as a focused, non-systematic evidence synthesis updated through 10 August 2026. It was designed to answer three questions: which passive mechanisms are repeatedly supported by empirical vernacular-building research; what Ethiopian and sub-Saharan African studies show about thermal comfort and adaptation; and which methods are used to document, assess and conserve vernacular built heritage. Targeted searches used combinations of 'vernacular architecture', 'thermal comfort', 'passive cooling', 'earthen dwelling', 'traditional housing', 'Ethiopia', 'East Africa', 'climate adaptation', 'architectural heritage' and 'vernacular conservation'. Discovery and verification were carried out through peer-reviewed publisher platforms and DOI/bibliographic records, with preference for English-language journal articles that described a clear method, documented case evidence or direct relevance to the thermal and conservation mechanisms under study.

Eligibility favoured recent work from 2019 onward while retaining earlier papers that established measurement approaches, thermal mechanisms or foundational heritage concepts. Peer-reviewed studies were screened for relevance to vernacular thermal performance, passive design, earthen construction, climate adaptation, Ethiopian architecture and

heritage conservation. Thirty-five studies were retained for the comparative synthesis in Table 1, including a strengthened set of Ethiopian and sub-Saharan African sources. Figure 6 summarizes the literature-selection logic, while foundational books and Ethiopia-specific documentary sources establish terminology and historical context outside the 35-study comparative set.

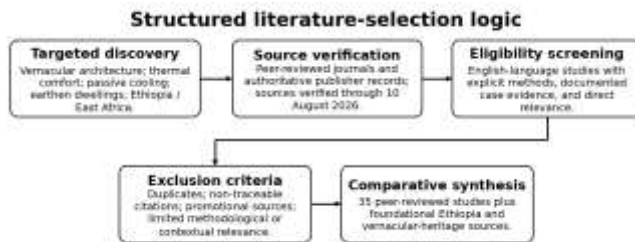


Figure 6. Structured literature-selection logic used for the comparative evidence synthesis.

Feature coding and thermal-mechanism interpretation

Case-study features were coded into six categories: (1) building form and exposure, (2) wall material and thickness, (3) roof geometry and covering, (4) openings and air paths, (5) internal organization and heat sources, and (6) material sourcing and maintainability. For each category, the analysis followed the chain documented feature -> plausible heat-transfer or environmental mechanism -> external empirical/simulation evidence -> heritage implication -> uncertainty. This sequence keeps observed architecture, physical interpretation and literature-supported inference analytically separate.

Cross-study triangulation

Cross-study triangulation is used to judge the convergence of architectural evidence and published thermal mechanisms. A mechanism is treated as strongly supported when the relevant Tukul feature is clearly documented and several measured or simulation studies report a physically consistent effect under reasonably comparable conditions. Support is classified as moderate when the effect is especially sensitive to material properties, geometry, ventilation, climate or occupant behaviour. The evidence-strength categories therefore express the consistency and physical plausibility of each mechanism and support the heritage interpretation summarized in Figure 7.

Methodological workflow



Figure 7. Methodological workflow linking field documentation, structured literature synthesis, feature coding, passive-mechanism interpretation, cross-study triangulation and conservation synthesis.

V. RESULTS AND DISCUSSION

Architectural morphology and environmental exposure

The dominant geometric characteristic is the circular plan beneath a steep conical roof (Figure 2). A circular perimeter avoids long orthogonal facades and distributes orientation continuously. Its environmental effect depends on surface-area-to-volume ratio, roof exposure, solar path, shading, surface absorptance and dwelling size. In the Kechema Tukul, the circular form is therefore interpreted as one element of a combined envelope strategy rather than as an isolated determinant of heat gain. Together with the roof overhang and relatively low wall height, it can reduce prolonged intense exposure of any single wall segment and distribute solar loading around the perimeter. This mechanism provides a clear basis for future geometric and solar-response analysis while remaining consistent with the documented architecture.

The circular plan also has a heritage consequence. It organizes the dwelling around a central post and interior activities rather than around a rectilinear structural grid. This spatial logic is visible in the plans with storage, hearth and sleeping zones arranged around the central support. Conservation of the external silhouette without the internal spatial organization would therefore preserve only part of the building tradition. The morphology should be documented as a relationship among plan, central support, roof geometry and patterns of use.

Prior studies support this integrated reading. Chandel et al. (2016) identify building form and orientation as recurring energy-related features, while Ergün and Bekleyen (2024) classify compactness and solar control among passive

strategies in hot-dry traditional architecture. The Kechema geometry is therefore interpreted as part of a broader envelope system in which circular form, roof overhang, wall material and opening pattern act together to moderate environmental exposure.

Earthen and wattle-and-daub walls: thermal storage, buffering and repairability

The wall system combines a timber or reed lattice with mud finishing, while some local variants also use thicker earthen or stone-containing construction (Figure 3). These walls can moderate heat transfer through heat capacity, thickness, porosity and moisture exchange. Where there is a marked day-night temperature swing, thermal storage can delay peak heat flow until outdoor conditions begin to cool. The most defensible conclusion is therefore that the earthen walling can buffer short-term temperature variation; the actual time lag and decrement factor depend on measured wall thickness and material properties.

Evidence from Singh et al. (2010), Rincón et al. (2019) and Hailu et al. (2021) supports the wider proposition that traditional massive or earthen envelopes can moderate exposure to outdoor extremes. Although wall compositions and climates differ among these studies, the recurring mechanism is consistent: wall mass, thickness, moisture condition and thermal properties influence heat storage, delay and surface-temperature response. For the Kechema Tukul, these parameters provide a clear basis for interpreting the earthen wall as both an environmental buffer and a conservation-sensitive material system.

From a conservation standpoint, mud finishing is also a sacrificial and renewable maintenance layer. Its compatibility with the underlying lattice, vapour behaviour and ease of local repair can be as important as nominal thermal conductivity. Replacing it with a dense, impermeable render may change moisture transport and repair practice even if the surface initially appears more durable. Correia and Walliman (2014) emphasize compatibility in earthen-built heritage interventions, making a strong case for material testing before substitution.

Figure 3 also shows a stone plinth or raised base. Its direct contribution to heat transfer is smaller than that of the wall and roof, but its conservation role is important because it helps separate earthen materials from splash water, runoff and biological attack. Protecting the lower wall from persistent

moisture can extend the service life of the envelope and reduce the need for major repair.

Conical thatched roof: solar protection and insulating depth

The conical roof is the most visually dominant part of the Tukul and one of the most important surfaces for solar control. Figures 3 and 5 show the steep geometry, radial timber framing, ring members and substantial grass-thatch covering. Together, the slope, overhang and fibrous roof layer shade the low wall, resist direct conductive heat transfer, trap air within the thatch and shed rain rapidly.

The thermal behaviour of thatch depends on thickness, compaction, moisture, ageing and workmanship. Its physical role is nevertheless well established: a dry, low-density fibrous layer contains air and resists conductive heat flow, while deep eaves can reduce direct solar load on walls and the doorway. Shanthi Priya et al. (2012), Salgin et al. (2017) and Widera (2021) provide comparative support for roof insulation and shading as passive strategies. In the Kechema Tukul, this mechanism is reinforced by the steep conical geometry, overhang and locally maintained roof assembly.

Heritage significance is especially high because roof performance depends on craft knowledge. The drawings identify the sequence of principal rafters, secondary rings or purlins, local tying materials and seasoned grass. Curk et al. (2025) argue that such skills are part of architectural heritage protection, not simply a means of reproducing appearance. If thatching knowledge is lost, conservation becomes dependent on substitute products and contractors who may not reproduce the original assembly or its hygrothermal behaviour.

Roof conservation should consequently address both fabric and process: availability of suitable grass, harvesting season, drying, bundling, fixing density, eaves detailing, replacement interval and safe repair access. These practical variables determine whether the roof remains a functioning environmental system. A future quantitative study should measure roof build-up, thermal resistance, internal surface temperature and heat flux through representative roof sections under dry and wet conditions.

Openings, roof-wall gap and natural ventilation

The documented houses generally use small openings: a low doorway and a narrow ventilation path close to the wall-roof

junction, visible in Figures 2 and 3. This arrangement can reduce direct solar penetration and wind-driven dust while regulating air exchange. Its thermal effect depends on timing: restricted openings can reduce hot daytime air entry, whereas evening and night-time ventilation can help release stored heat. The doorway, upper air path and conical roof therefore operate together as a climate-responsive ventilation arrangement whose effectiveness varies with weather, wind and household use.

The conical roof geometry creates an upper volume in which warmer air can accumulate, while the doorway and roof-wall opening establish a potential pathway for wind- and buoyancy-assisted air movement. The strength of this pathway depends on effective opening area, doorway condition, vertical separation, wind pressure and internal obstructions. The roof-wall gap is therefore interpreted as a controlled ventilation detail whose contribution varies with weather and household operation. Air-speed measurement, tracer-gas methods and door-position records would provide a useful quantitative extension of this mechanism in subsequent field studies.

This cautious interpretation is supported by comparative studies. Passive ventilation is widely reported as part of climate-responsive vernacular design, but its usefulness varies with outdoor conditions and occupant control. Hailu et al. (2021), Chkeir et al. (2024) and Ibrahim and Abdullah (2026) demonstrate the value of combining environmental monitoring with building comparison. For Kechema, a similar protocol would allow the role of the doorway and eaves gap to be distinguished from the effects of thermal mass and roof insulation.

Interior organization, hearth and diurnal adaptation

The plans show that the Tukul is an occupied environmental system in which sleeping, storage, hearth and sometimes animal-related functions share the compact enclosure. The partitioned arrangement in Figure 4 demonstrates variation within the tradition. The central hearth provides deliberate heat during cool periods and also makes ventilation and indoor environmental quality integral to the architectural interpretation. Widera (2021) emphasizes this relationship in sub-Saharan vernacular dwellings, where thermal comfort, air movement and combustion-related exposure need to be considered together. Recording cooking periods, fuel use, occupancy, door position and indoor-air-quality indicators would therefore provide a valuable extension of the heritage and environmental assessment.

Internal partitions may also alter air movement and radiant exchange. The partitioned example indicates that variations exist within the Tukul tradition, which argues against treating one drawing as a universal prototype. Heritage documentation should record these variants before modernization or abandonment removes them. A future field campaign should select multiple representative houses, including partitioned and unpartitioned types, rather than relying on one dwelling.

Local materials, embodied impacts and conservation economy

Local material use is a defining feature of the Kechema Tukul. Timber or reeds, earth, stone and grass are assembled with relatively low-technology processes, as shown in Figures 3 and 5. These materials should not be described simplistically as having no environmental impact: harvesting, transport, maintenance frequency and land use still matter. Their main advantage is that renewable or minimally processed resources can reduce dependence on energy-intensive industrial products and can keep routine maintenance within the local construction economy.

Praseeda et al. (2014) demonstrate why embodied and operational effects should be considered together, while Carlos et al. (2022) show that earthen-heritage interventions must also account for material compatibility, maintenance and community knowledge. For Tukul conservation, substitution should therefore be assessed against thermal compatibility, moisture behaviour, structural role, durability, embodied impact, availability, repair skill and cultural acceptance. A more industrial material is not automatically a more sustainable or conservation-compatible choice.

The social dimension is equally important. When local repair knowledge is retained, small defects can be addressed incrementally. When skills and materials disappear, maintenance may be delayed until major replacement is required. Conservation policy should therefore support material supply chains and craft transmission, not only individual demonstration buildings. This is consistent with recent vernacular-heritage research that treats living knowledge as part of the resource being conserved.

Cross-study triangulation of the identified thermal mechanisms

Table 2 summarizes cross-study triangulation of the main mechanism across the documented Tukul features and the thermal mechanisms. The evidence-strength rating expresses comparative literature. confidence in the physical plausibility and consistency of each

Table 2. Cross-study triangulation of thermal mechanisms inferred from the Kechema Tukul evidence.

Case feature	Interpreted mechanism	External support	Evidence strength	Key uncertainty
Circular compact form	Distributes wall exposure and reduces long exposed facades	Chandel et al. 2016; Ergün & Bekleyen 2024	Moderate	Exact solar benefit requires geometry/orientation modelling.
Earthen/mud walling	Stores and delays heat; buffers diurnal change	Singh et al. 2010; Rincón et al. 2019; Hailu et al. 2021	Strong for mechanism	Sensitivity to wall thickness, composition, moisture and maintenance condition.
Deep thatched conical roof	Shades walls; resists roof heat flow; drains rainfall	Shanthi Priya et al. 2012; Salgin et al. 2017; Izadpanahi et al. 2021	Strong for mechanism	Thatch thickness, conductivity and wet-state performance unknown.
Small doorway/openings	Limits direct solar and hot-air entry during daytime	Chandel et al. 2016; Al-Hashim et al. 2024	Moderate	May reduce beneficial ventilation; control strategy not documented.
Roof-wall ventilation gap	Potential buoyancy/wind-driven air exchange	Hailu et al. 2021; Widera 2021; Chkeir et al. 2024; Ibrahim & Abdullah 2026	Moderate	Sensitivity to effective opening area, wind pressure, occupancy and door operation.
Central hearth	Potential night-time heat source; indoor-air-quality interaction	Case drawing; Widera 2021; general heat/ventilation principles	Moderate	Heat gain, CO/PM exposure and smoke-removal conditions require field monitoring.
Local renewable materials	Potentially low processing and repair energy	Praseeda et al. 2014; Carlos et al. 2022	Moderate to strong	Life-cycle impacts depend on sourcing and replacement rate.

Comparison with previous research

The Kechema case converges most strongly with previous research in the combined use of mass, roof insulation/shading and restricted openings. Singh et al. (2010), Hailu et al. (2021) and Widera (2021) provide empirical parallels for environmental moderation in traditional dwellings, while Rincón et al. (2019) is particularly relevant to earthen housing in sub-Saharan Africa. Yadeta et al. (2023) and Asres et al. (2026) add Ethiopia-specific evidence that adaptive comfort and behavioural responses require local calibration. These latter studies concern naturally ventilated residential and social housing rather than Tukul dwellings, so they are used to justify

measurement strategy rather than as direct performance analogues.

With respect to modernization, the Kechema interpretation is consistent with Shastry et al. (2014) and Henna et al. (2021), who show that inherited performance can change when materials, climate or building practices change. Asfha et al. (2026) adds an Ethiopian conservation perspective by demonstrating the value of systematic vernacular documentation under contemporary transformation. Corrugated sheet roofing, dense cement render, large unshaded openings and rectilinear additions are considered as intervention types whose thermal, moisture and heritage

consequences should be evaluated carefully. The appropriate conservation response is to test proposed changes against the functioning of the whole envelope and the cultural values carried by its fabric and craft.

In heritage methodology, the study aligns with Arias Tapiero et al. (2025) by emphasizing systematic characterization before intervention. It also parallels Curk et al. (2025) in treating construction knowledge as a heritage asset and Sánchez-Calvillo et al. (2025) in making feature-based assessment criteria explicit. The Tukul case adds a thermal-performance dimension to this heritage framing by showing that construction attributes can be prioritized partly because they support environmental moderation.

Ethiopian studies add an important cultural dimension. Datta and Gruber (2021), Sahle and Saito (2021), and Kebede et al. (2024) show that regional building traditions and cultural landscapes cannot be explained by climate alone. The Kechema

Tukul should therefore not be treated as a generic hot-climate passive house. Its heritage value lies in the particular combination of Oromo-area construction practice, local resources, family use and environmental response documented in this case study.

Heritage significance and conservation priorities

Table 3 translates the thermal and heritage interpretation into a transparent conservation-priority framework. Five criteria are considered: (1) typological distinctiveness, (2) plausible environmental function, (3) material/craft authenticity, (4) vulnerability to loss or incompatible change, and (5) difficulty of replacement or reversibility. 'Very high' is used where at least four criteria are strongly present; 'High' where three are strongly present; and 'Moderate to high' where two or three are present but vulnerability is lower or replacement is more reversible. The categories are heuristic priorities for field verification, not statutory heritage grades.

Table 3. Proposed conservation priorities based on typological, environmental, authenticity, vulnerability and replaceability criteria.

Attribute	Priority	Why it matters	Potential vulnerability	Recommended action
Conical thatch roof assembly	Very high	Dominant silhouette; craft-intensive; principal solar/rain shield	Potential: loss of thatching skill, material scarcity, replacement with incompatible sheets	Document assembly; support grass supply and craft training; test compatible fire/rain improvements.
Earthen/wattle-and-daub wall	Very high	Local material identity; moisture/thermal buffering; repair tradition	Potential: impermeable render, erosion, poor plinth maintenance	Use compatible earthen repairs; record thickness and mix; protect base from water.
Circular plan and central-post system	High	Defines typology, spatial logic and roof support	Potential: rectilinear extensions; removal of central post	Record variants; design additions as legible and structurally independent where possible.
Eaves/roof-wall ventilation detail	High	Potential passive air path and weathering detail	Potential: sealing during modernization; uncontrolled gaps	Measure airflow before alteration; retain controlled high-level ventilation where safe.
Single small doorway/opening pattern	Moderate to high	Characteristic facade and solar/dust control	Potential: large unshaded openings introduced for modern use	Evaluate daylight/ventilation need; add shaded openings rather than indiscriminate enlargement.
Stone plinth / raised base	High	Protects vulnerable earthen fabric from water	Potential: burial by raised ground levels; loss during repair	Maintain drainage and separation from splash water.

Attribute	Priority	Why it matters	Potential vulnerability	Recommended action
Craft knowledge and maintenance cycle	Very high	Intangible heritage enabling continued use and repair	Potential: loss of skilled builders and changing aspirations	Record oral/visual construction knowledge; create community-based transmission programmes.

Climate-change resilience and adaptive limits

The Tukul's passive logic is most plausible where daytime heat can be delayed, roof solar load can be limited and cooler periods remain available for heat release. Climate change may alter the balance of these mechanisms as night-time temperatures, rainfall intensity and material moisture conditions change. Balcha et al. (2024) document substantial seasonal rainfall variability at the East Shewa zonal scale, reinforcing the importance of drainage, roof maintenance and wet-season material behaviour in climate-responsive conservation.

Potential adaptations include improved drainage, sacrificial earthen coatings, controlled high-level ventilation, shaded daylight openings, insect screening, safer hearth arrangements and carefully tested roof improvements. Sheet roofing, impermeable render or substantially enlarged openings should be evaluated for vapour behaviour, solar loading, ventilation and heritage compatibility before wider application. A condition-based conservation approach can use these criteria to guide compatible adaptation while retaining the material and environmental logic of the Tukul.

This position is consistent with Sanagustín-Fons et al. (2025), who connect heritage architecture with climate adaptation, and with the resilience perspective of Henna et al. (2021). Future warming may weaken some inherited passive mechanisms, especially if night-time temperatures rise or material durability changes. Establishing the extent of that change requires long-term field monitoring rather than description alone.

VI. LIMITATIONS

The study is qualitative and case-specific, with conclusions derived from architectural documentation, mechanism-based interpretation and cross-study triangulation. Material properties, workmanship, maintenance condition, household use and local microclimate can vary among Tukul houses and influence environmental behaviour. The conservation-priority

framework should therefore be applied as a context-sensitive guide and locally calibrated when used for building-level intervention planning.

The comparative literature spans different climates, building types and assessment methods. Its value lies in identifying consistent physical mechanisms and heritage principles rather than producing a single transferable performance value. This scope supports a robust qualitative interpretation while keeping the conclusions closely tied to the documented Kechema architecture.

VII. CONCLUSIONS

The Kechema Tukul demonstrates a coherent passive-thermal logic rooted in the interaction of form, material and use. The circular plan, earthen or wattle-and-daub walls, deep conical thatch, restricted openings, roof-wall air path, hearth and locally sourced materials operate as a connected environmental system that supports solar protection, thermal buffering, insulation and controlled air exchange.

Cross-study triangulation with Ethiopian, sub-Saharan African and wider vernacular-building research strengthens the interpretation of these mechanisms. The findings show that the environmental response of the Tukul is produced by the combined envelope rather than by any single feature, and that climate, occupancy, maintenance and material condition shape how the system performs in practice.

The heritage significance of the Tukul therefore extends beyond its familiar circular silhouette. Earthen finishes, thatch assembly, timber framing, stone base, ventilation details, construction sequence and maintenance skills are both environmental components and records of living building practice. Conservation strategies should protect these relationships through compatible repair, careful material substitution and continued support for local craft knowledge.

The study establishes a practical heritage framework in which architectural documentation, passive environmental reasoning and conservation assessment are integrated. For Kechema Ward, this framework identifies the roof assembly, earthen wall system, raised base, controlled openings and construction knowledge as priority attributes for climate-responsive conservation. The same approach can inform the assessment of comparable vernacular settlements where environmental performance and cultural continuity are closely linked.

Future scope

Further research can extend the framework through seasonal monitoring of representative partitioned and unpartitioned Tukul houses, occupant-use documentation, indoor-air-quality assessment around hearth operation and comparison with contemporary rural dwellings. Material characterization and calibrated hygrothermal or whole-building simulation can then support future-climate assessment and the testing of compatible conservation measures.

A wider georeferenced inventory of Tukul variants, building condition, material supply and craft knowledge would strengthen heritage management at settlement scale and help evaluate climate-responsive adaptations before they are generalized across the region.

Declarations

CRediT authorship contribution statement: Eswara Rao Petta: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Resources, Writing - original draft, and Writing - review & editing. Viswanadh Kumar G.: Supervision, Validation, Methodology, and Writing - review & editing. Both authors read and approved the final manuscript. Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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Ethics statement: The study is based on author-prepared architectural documentation and published literature and falls outside the scope of human- or animal-subject experimental research.

Consent for publication: The figures consist of author-prepared architectural drawings and derived analytical graphics suitable for scholarly publication.

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